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Using Space Weather Variability in Evaluating the Radiation Environment Design Specifications for NASA's Constellation Program

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ABSTRACT

NASA's Constellation program, initiated to fulfill the Vision for Space Exploration, will create a new generation of vehicles for servicing low Earth orbit, the Moon, and beyond. Space radiation specifications for space system hardware are necessarily conservative to assure system robustness for a wide range of space environments. Spectral models of solar particle events and trapped radiation belt environments are used to develop the design requirements for estimating total ionizing radiation dose, displacement damage, and single event effects for Constellation hardware.

We first describe the rationale in using the spectra chosen to establish the total dose and single event design environment specifications for Constellation systems. We then compare variability of the space environment to the spectral design models to evaluate their applicability as conservative design environments and potential vulnerabilities to extreme space weather events.

SPE DESIGN ENVIRONMENT

SPE design environments for Constellation lunar applications must provide the mission duration proton fluence that space systems will experience during extended periods in the interplanetary environment unprotected by the geomagnetic shielding of the Earth's magnetic field. The Constellation SPE design environments for hardware shown in Figure 1 are two times the worst week and worst 5-minute spectra given by the 1996 version of the Cosmic Ray Effects on Microelectronics (CREME96) model [*Tylka et al.*, 1997a]. CREME96 SPE environments are obtained from GOES 7 proton flux measurements during the series of coronal mass ejection events in October of 1989 [*Tylka et al.*, 1997b, 1996] that are widely used by the engineering community as severe design environments. Worst week CREME96 environments are given by the average flux measured over 180 hours beginning at 1300 UT on 19 October 1989 and the 5-minute environment is the average flux over the worst 5-minute period of that event.

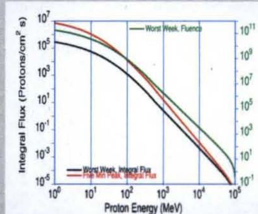


Figure 1. The SPE Design Environment. Integral flux and fluence of worst week environment and integral peak flux environment.

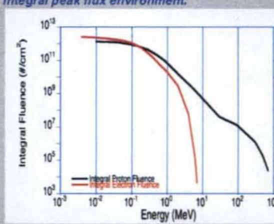


Figure 2. Design Environment (integral fluence) for proton and electron trapped radiation environments

RADIATION BELT DESIGN ENVIRONMENT

Constellation trapped radiation belt design environments are currently based on the AP-8, AE-8 solar maximum models [*Sawyer and Vette*, 1976; *Vette*, 1991]. Proton and electron fluence for a single transit through the Earth's radiation belts are given in Figure 2 based on a 385 km x 385,000 km x 28.5 degree inclination orbit. Spacecraft will spend approximately 4 hours in the radiation belts out of the four to five day transit time from the Earth to the Moon.

The trapped proton and electron fluence dominates the integral fluence at energies less than ~1 MeV while the solar proton contributions dominate the design environments at greater energies.

VARIABILITY OF SOLAR PARTICLE EVENT ENVIRONMENT

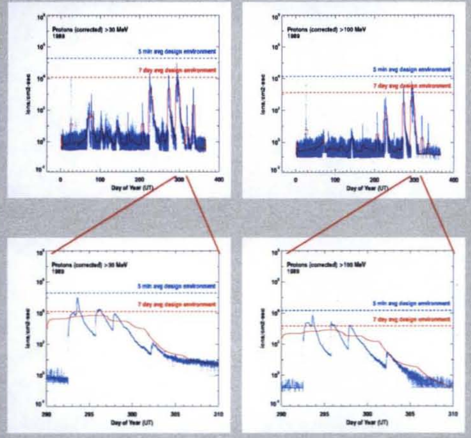


Figure 3. SPE Design Environments Compared to 1989 GOES-7 Proton Flux Measurements.

Measured >30 MeV and >100 MeV proton flux from the GOES 7 satellite is given for (top) the complete year 1989 and (bottom) detail for the October 1989 SPE events.

SPE worst week and 5-minute design environments exceed 7-day and 5-minute averages of the measured flux throughout 1989, demonstrating the conservative nature of the Constellation SPE design environments.

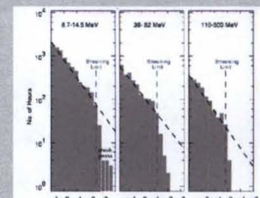


Figure 4. SPE Streaming Limits. Hour average proton flux for ~11 year period [from Reames, 2004].

Solar proton flux streaming from shock fronts is limited by wave particle interactions [*Ng and Reames*, 1994, *Reames and Ng*, 1998] establishing an upper bound for SPE total dose environments in interplanetary space.

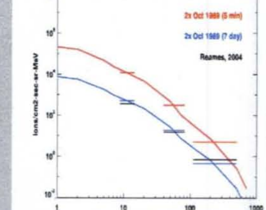


Figure 5. Constellation SPE Design Environments and Streaming Limits.

Constellation 5-min (red) and 7-day (blue) environments are compared to the *Reames* [2004] streaming limits (black) for SPE proton flux. For comparison, Constellation SPE Design Environments are integrated over the same GOES 7 energy bands used by *Reames*.

VARIABILITY OF TRAPPED RADIATION ENVIRONMENT

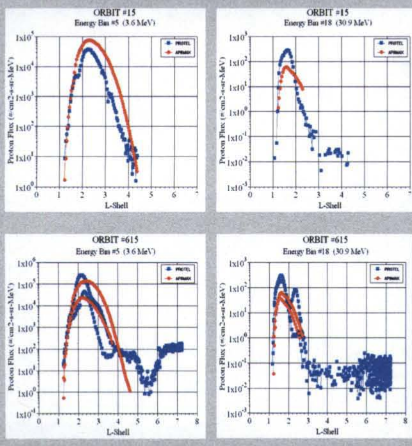


Figure 6. CRRES Proton Telescope (blue) Measurements Compared to AP-8 Solar Maximum (red) Model Values.

Proton flux at 3.6 MeV and 30.9 MeV measured by the Proton Telescope (PROTEL) instrument during Orbit 15 of the Combined Release and Radiation Effects Satellite (CRRES) represents a radiation belt transit environment during a quiescent period.

In comparison, Orbit 615 gives a representative disturbed period following the onset of a strong geomagnetic storm. The new proton belt generated during the March 1991 geomagnetic storm is evident in the 30.9 MeV channel of the Orbit 615 data.

The mean AP-8 Solar Maximum environment is sufficient for quiescent periods at low energies although the model underestimates the Orbit 15 environment in the inner belts. AP-8 underestimates the proton flux during disturbed periods at both energies.

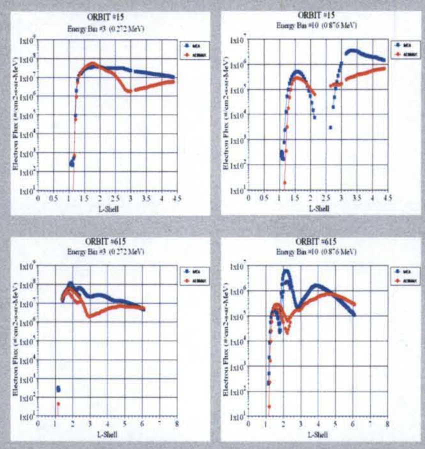


Figure 7. CRRES Magnetic Electron Spectrometer (blue) Measurements Compared to AE-8 Solar Maximum (red) Model Values.

The quiet Orbit 15 and disturbed Orbit 615 272 keV and 876 keV electron environments exceed the AE-8 Solar Maximum design environments in both of these cases.

While AE-8 may be acceptable as a mean representation of electron flux during the maximum phase of the solar cycle, it is not adequately conservative for use in specifying electron environments for single transits of the Earth's radiation belts.

DISCUSSION AND SUMMARY

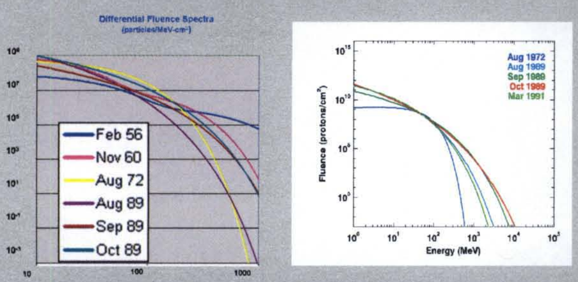
SPE Event Fluence Comparison

Event	Max >30 MeV flux (#/cm2-s-sr)	>30 MeV fluence (#/cm2)
1859/09/01	5×10^4	19×10^9
1960/11/15	-----	9×10^9
	hardware spec	
1946/07/25	-----	6×10^9
1972/08/04	2×10^4	5×10^9
2000/07/12	------	4.3×10^9
1989/10/19	------	4.2×10^9
2001/11/04	------	3.4×10^9
2003/10/28	4.5×10^3	3.4×10^9
2000/08/00	------	3.2×10^9
1959/07/14	-----	2.3×10^9
1991/03/22	------	1.8×10^9
1989/08/12	------	1.4×10^9
1989/09/29	------	1.4×10^9
2001/09/24	------	1.2×10^9
2005/01/15	------	1.0×10^9

[Sources: *Smart and Shea*, 2002; *Reedy*, 2006; *Smart et al.*, 2005]

Figure 8. >30 MeV Proton Fluence for Extreme SPE Events.

Constellation worst week environments establish the total ionizing dose for hardware due to solar proton events. The design environment is consistent with large proton events recorded during the space age and is within ~2x to ~3x the 1859 Carrington event fluence considered to be the worst case in the past ~400 years [*McCracken et al.*, 2001a,b].



a) b)

Figure 9. Spectral Hardness Comparison for Selected Large SPE Events. (a) Differential fluence spectra for selected events demonstrates both integrated flux and hardness variations for individual events (from Turner, 2005). (b) Proton fluence normalized to the Carrington event >30 MeV proton fluence [adapted from Townsend et al., 2006].

SOLAR PARTICLE EVENT ENVIRONMENT

- Constellation 7-day SPE environments are based on extreme solar energetic particle event environments which exceed the streaming limits at the lower energies and are on the order of the streaming limits at the highest energies.

- The SPE Design Environment >30 MeV fluence exceeds the >30 MeV fluence observed for most of the large SPE events during the historical space age where in-situ measurements of SPE flux are available and is within a factor of ~2x to ~3x of the large 1859 event fluence that has been inferred from ice core records.

- SPE environments are sufficiently robust for use in designing systems for long term use in environments where dose and dose rate effects are dominated by SPE environments.

TRAPPED RADIATION ENVIRONMENT

- Current Constellation trapped radiation environments are derived from AP-8, AE-8 Solar Maximum models which represent the mean environments present during the active phase of the solar cycle. While Constellation hardware exposure to the Earth's radiation belts in transit to and from the Moon will only be on the order of approximately four hours, it is important to establish design environments which represent the extremes that may be encountered during transit period instead of the mean environments represented by the AP-8/AE-8 models.

- Modification of the trapped radiation belt environments are warranted to assure that Constellation systems are adequately designed for total dose and dose rate effects during radiation belt transits.

ACKNOWLEDGEMENTS

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